

1N:24

43490

P-34

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(NASA-TM-106862) EFFECTS OF
DELAMINATIONS ON THE DAMPED DYNAMIC
CHARACTERISTICS OF COMPOSITE
LAMINATES: MECHANICS AND
EXPERIMENTS (NASA. Lewis Research
Center) 34 p

N95-23258

Unclass

G3/24 0043490

February 1995



National Aeronautics and
Space Administration

**EFFECTS OF DELAMINATIONS ON THE
DAMPED DYNAMIC CHARACTERISTICS OF COMPOSITE LAMINATES:
MECHANICS AND EXPERIMENTS**

by

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ABSTRACT

Analytical and experimental work is presented on the damped free-vibration of delaminated laminates and beams. A laminate theory is developed where the unknown kinematic perturbations induced by a delamination crack are treated as additional degrees of freedom. The generalized stiffness, inertia and damping matrices of the laminate are formulated. An analytical solution is developed for the prediction of natural frequencies, modes and modal damping in composite beams with delamination cracks. Evaluations of the mechanics on various cantilever beams with a central delamination are performed. Experimental results for the modal frequencies and damping of composite beams with a single delamination are also presented and correlations between analytical predictions and measured data are shown. The effects of delamination vary based on crack size, laminate configuration, and mode order. The implications of the mechanics in developing delamination detection techniques are also discussed.

INTRODUCTION

Along with the continuous competing requirements for improving the weight, interdisciplinary performance, and reliability of composite components, the development of real-time non-destructive "health-monitoring" techniques based on the global dynamic characteristics of the composite structures is receiving growing attention (Lee et al. 1987; Tracy and Pardoen, 1989; Grady and Meyn, 1989; Raju et al., 1992). Among them, the capability to detect delaminations by monitoring changes in the dynamic characteristics or in the dynamic response of the structure seems to be an attractive technique. Yet, in order to realize the full benefits of such techniques, analytical models are required which will quantify and provide valuable insight on the dynamic characterization of composites with induced delaminations. Consequently, this paper presents recent developments in composite mechanics for predicting the delamination effects in composite laminates and laminated beams, together with experimental studies.

Although significant work has been reported in the general area of delamination prediction and growth, some research has been reported on the prediction of delamination effects on structural response. Tracy and Pardoen (1989), Nagesh Babu and Hanagud (1990), Paolozzi and Peroni (1990), and Shen and Grady (1992) have analyzed the effects of a single delamination on the natural frequencies and modes of composite beams using the "four-region" approach, that is, the delaminated beam was divided into four regions and beam theory was applied to each region. Tenek et. al. (1993) used a similar approach for plates. On a parallel approach, Anastasiadis and Simites (1991) and Simites (1993) have addressed the buckling of delaminated beams. Barbero and Reddy (1991) have also reported a layerwise plate theory for the analysis of delaminated laminates, which was later extended by Lee et. al. (1992) on a finite element based buckling analysis of composite beams with multiple delaminations. To the authors' best knowledge, no analytical or experimental work has been reported quantifying the effects of delaminations on the damping of composite laminates/structures.

The present method involves generalized kinematic assumptions and represents the discontinuities in the in-plane and through-the-thickness displacements, as well as, the discontinuities in the slopes of the in-plane displacements across each delamination crack. The induced discontinuities are treated as additional degrees of freedom. The laminate stiffness, mass, and damping matrices are generalized and expanded to include additional terms which represent the effects of delamination on the dynamic properties of the delaminated composite. Hence, a unified and inclusive laminate theory is developed which can handle either pristine, or delaminated laminates with single or multiple delaminations. The present mechanics include both intralaminar and interlaminar effects, hence, they entail the potential to provide accurate predictions of delamination effects on the dynamic characteristics.

To illustrate the merit of this generalized laminate theory, the dynamic equations of motion are formulated and an exact methodology for predicting the free vibration of composite beams with a delamination is developed. Moreover, the modal frequencies and damping of [0/90/45/-45]_s and [45/-45/90/0]_s T300/934 cantilever beams with various sizes of simulated delamination cracks were measured. Predicted results are correlated to these experimental data, as well as, with other reported natural frequency measurements. Both analytical and experimental parametric studies assess the effects of delamination size and laminate configuration on modal frequencies, shapes, and laminate damping. The results provide valuable insight into the problem, and are envisioned to facilitate the interpretation of future experimental results, as well as, the development of effective "health monitoring" techniques for improved reliability in composite structures.

LAMINATE MECHANICS

The present section presents mechanics for laminates with interlaminar delamination cracks. The kinematic assumptions are extended to represent the discontinuities in both in-plane and through-the-thickness displacement fields (Fig. 1) induced by the presence of one or several (N_d) delaminations between the composite plies.

$$\begin{aligned}
u(x,y,z) &= u^o(x,y) + \alpha_x^o(x,y)z + \sum_{k=1}^{N_d} (u^k(x,y)H(z-z_k) + \alpha_x^k(x,y)zH(z-z_k)) \\
v(x,y,z) &= v^o(x,y) + \alpha_y^o(x,y)z + \sum_{k=1}^{N_d} (v^k(x,y)H(z-z_k) + \alpha_y^k(x,y)zH(z-z_k)) \\
w(x,y,z) &= w^o(x,y) + \sum_{k=1}^{N_d} w^k(x,y)H(z-z_k)
\end{aligned} \tag{1}$$

where: u , v , w are the in-plane and through-the-thickness displacements; α_x and α_y are slopes of the in-plane displacement along the x and y axes; H is the Heaviside's step function; superscript o indicates midplane quantities, and superscript k indicates the new degrees of freedom describing the kinematic discontinuities across the k -th delamination; z_k is the distance of the k -th delamination from the mid-plane. In the absence of delaminations, the theory may reduce either to classical laminate theory, or to a discrete-layer type of laminate theory (Alam and Asnani, 1986; Barbero et. al, 1990; Saravanos, 1993).

Based on the above kinematic assumptions, the intralaminar and interlaminar strains through the thickness of the laminate are:

$$\begin{aligned}
\epsilon_{ci} &= \epsilon_i^o + k_i z + \sum_{k=1}^{N_d} \epsilon_i^k H(z-z_k) + k_i^k z H(z-z_k) \quad i=1,2,6 \\
\epsilon_{ci} &= \sum_{k=1}^{N_d} \epsilon_i^k \hat{\delta}(z-z_k) + \alpha_i^k z \hat{\delta}(z-z_k) \quad i=4,5 \\
\epsilon_{c3} &= \sum_{k=1}^{N_d} \epsilon_3^k \hat{\delta}(z-z_k)
\end{aligned} \tag{2}$$

where $\hat{\delta}$ is the Dirac's impulse function. In the context of the present formulation, interlaminar strains exist across the delamination cracks only. In the above equations the midplane strains and curvatures $\{\epsilon^o\}$ and $\{k\}$ are traditionally defined as

$$\begin{aligned}
\epsilon_1^o &= u_x^o, & \epsilon_2^o &= v_y^o, & \epsilon_6^o &= u_y^o + v_x^o \\
k_1 &= \alpha_{xx}^o = -w_{xx}^o, & k_2 &= \alpha_{yy}^o = -w_{yy}^o, & k_6 &= \alpha_{xy}^o + \alpha_{yx}^o = -2w_{xy}^o
\end{aligned} \tag{3}$$

The comma in the subscripts indicates differentiation. As seen in eq. (2), additional generalized strains $\{\epsilon^k\}$ and $\{k^k\}$ exist which describe induced changes in the strain field as a result of the k th delamination,

$$\begin{aligned} \epsilon_1^k &= u_{,x}^k, & \epsilon_2^k &= v_{,y}^k, & \epsilon_6^k &= u_{,y}^k + v_{,x}^k \\ k_1^k &= \alpha_{xx}^k - w_{,xx}^k, & k_2^k &= \alpha_{yy}^k - w_{,yy}^k, & k_6^k &= \alpha_{xy}^k + \alpha_{yx}^k - 2w_{,xy}^k \\ \epsilon_3^k &= w^k & \epsilon_4^k &= v^k & \epsilon_5^k &= u^k \end{aligned} \quad (4)$$

The corresponding generalized laminate stresses are the resultant axial forces and moments per unit depth, $\{N\}$ and $\{M\}$ respectively, for the whole laminate,

$$\langle \{N^o\}, \{M^o\} \rangle = \int_{-h}^h \{\sigma\} \langle 1, z \rangle dz \quad (5)$$

and for each delaminated section

$$\langle \{N^k\}, \{M^k\} \rangle = \int_{-h}^h \{\sigma\} H(z-z_k) \langle 1, z \rangle dz \quad k=1, \dots, N_d \quad (6)$$

where h is the laminate half-thickness, N_d the number of delaminations through the thickness, and superscripts o and k indicate pristine and delaminated regions respectively. Combining eqs. (2), (5) and (6) the generalized laminate stresses are related to the laminate strains as follows:

$$\begin{aligned} \{N^o\} &= [A]\{\epsilon^o\} + [B]\{k\} + \sum_{k=1}^{N_d} [P^k]\{\epsilon^k\} + [R^k]\{k^k\} \\ \{M^o\} &= [B]\{\epsilon^o\} + [D]\{k\} + \sum_{k=1}^{N_d} [R^k]\{\epsilon^k\} + [T^k]\{k^k\} \end{aligned} \quad (7)$$

$$\begin{aligned} \{N^k\} &= [P^k]\{\epsilon^o\} + [R^k]\{k\} + \sum_{l=1}^{N_d} [A^k]\{\epsilon^l\} + [B^k]\{k^l\} \\ \{M^k\} &= [R^k]\{\epsilon^o\} + [T^k]\{k\} + \sum_{l=1}^{N_d} [B^k]\{\epsilon^l\} + [D^k]\{k^l\} \quad k=1, \dots, N_d \end{aligned} \quad (8)$$

The resultant laminate stiffness matrices in the above equations are,

$$\begin{aligned}
 [A], [B], [D] &= \sum_{j=1}^{N_l} \int_{-h}^h [Q_c]_j \langle 1, x, x^2 \rangle dz \\
 [P^h], [R^h], [T^h] &= \sum_{j=1}^{N_l} \int_{-h}^h [Q_c]_j H(z-z_k) \langle 1, x, x^2 \rangle dz \\
 [A^h], [B^h], [D^h] &= \sum_{j=1}^{N_l} \int_{-h}^h [Q_c]_j H(z-z_k) H(z-z_l) \langle 1, x, x^2 \rangle dz
 \end{aligned} \tag{9}$$

where N_l is the number of plies and $[Q_c]$ is the ply stiffness matrix. The 3 by 3 matrices $[A]$, $[B]$ and $[D]$ describe the extensional, coupling and flexural laminate stiffness of the pristine laminate. The other six matrices are new and describe the changes in axial, coupling and flexural laminate stiffness as a result of the delaminations. These additional stiffness matrices increase the stored strain energy in the delaminated area resulting in a loss of the overall rigidity.

The dissipated strain energy δW_L per unit area of the laminate (excluding friction effects) is:

$$\delta W_L = \frac{1}{2} \int_{-h}^h 2\pi \{\epsilon_c\}^T [Q_c] [\eta_c] \{\epsilon_c\} dz \tag{10}$$

where $[\eta_c]$ is the damping matrix (loss factors) of each composite ply (Saravanan and Chamis, 1990). Combining eqs. (2) and (10), then integrating through the thickness, the dissipated strain energy in the laminate (excluding friction effects) is expressed in a separable form of strains and laminate damping matrices

$$\delta W_L = \frac{1}{2} \{ \epsilon^o, k^o, \dots, \epsilon^k, k^k \} \begin{bmatrix} [A_d] & [B_d] & \dots & [P_d^k] & [R_d^k] \\ [B_d] & [D_d] & \dots & [R_d^k] & [T_d^k] \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ [P_d^k] & [R_d^k] & \dots & [A_d^k] & [B_d^k] \\ [R_d^k] & [T_d^k] & \dots & [B_d^k] & [D_d^k] \end{bmatrix} \begin{Bmatrix} \epsilon^o \\ k^o \\ \vdots \\ \epsilon^k \\ k^k \end{Bmatrix} \quad (11)$$

As in the case of stiffness matrices, the presence of a delamination crack alters the dissipated energy in the laminate in two discrete ways: (1) by changes in the damping properties of the delaminated sublaminates, expressed with the introduction of additional damping matrices in eq. (11); and (2) by the simultaneous changes in the average strains and curvatures of each sublaminate. The damping laminate matrices are:

$$\begin{aligned} [A_d], [B_d], [D_d] &= \sum_{j=1}^{N_l} \int_{-h}^h 2\pi [\mathcal{Q}_d] [\eta_d] \langle 1, x, x^2 \rangle dz \\ [P_d^k], [R_d^k], [T_d^k] &= \sum_{j=1}^{N_l} \int_{-h}^h 2\pi [\mathcal{Q}_d] [\eta_d] H(x-t_k) \langle 1, x, x^2 \rangle dz \\ [A_d^k], [B_d^k], [D_d^k] &= \sum_{j=1}^{N_l} \int_{-h}^h 2\pi [\mathcal{Q}_d] [\eta_d] H(x-t_k) H(x-t_l) \langle 1, x, x^2 \rangle dz \end{aligned} \quad (12)$$

The through-the-thickness location of the delamination is reflected in the additional stiffness, damping and mass matrices indicated with superscripts k and kl .

In addition to changes in the hysteretic damping of the laminate, additional energy is dissipated from friction along the interfaces of each delamination crack due to their relative motion, expressed by u^k and v^k , across the interfaces of each crack. The friction effects are not included in the present paper, however, the mechanics have certain provisions and related work will be reported in future work. Nevertheless, the significance of interfacial friction is assessed in the applications sections via comparisons with experimental results.

COMPOSITE BEAMS WITH DELAMINATION

The present section describes the application of the laminate mechanics in developing an analytical solution to model the dynamic characteristics of general composite beams with a single delamination. This exact, yet computationally inexpensive model provides valuable insight into the effects of delaminations on the dynamic characteristics of composite structures. Moreover, it is timely appropriate because most efforts in this area have been focused on composite beam specimens. The development of structural mechanics for other configurations will be addressed in the near future.

Considering a beam with k delaminations extending through the whole depth as shown in Fig. 2, in free flexure conditions (only the axial forces/moments N_x , M_x , N_x^k , M_x^k are nonzero), effective constitutive equations may be derived by inverting eqs. (7-8), then imposing the free-flexure conditions ($N_y = M_y = N_y^k = M_y^k = N_{xy} = M_{xy} = N_{xy}^k = M_{xy}^k = 0$). Inverting once more the remaining equations, the equivalent laminate relations take the form:

$$\begin{aligned}
 N_x^{\infty} &= A_{11}^{\infty} \epsilon_x^{\infty} + B_{11}^{\infty} k_x^{\infty} + \sum_{k=1}^{N_d} P_{11}^{*k} \epsilon_x^k + R_{11}^{*k} k_x^k \\
 M_x^{\infty} &= B_{11}^{\infty} \epsilon_x^{\infty} + D_{11}^{\infty} k_x^{\infty} + \sum_{k=1}^{N_d} R_{11}^{*k} \epsilon_x^k + T_{11}^{*k} k_x^k \\
 N_x^k &= P_{11}^{*k} \epsilon_x^{\infty} + R_{11}^{*k} k_x^{\infty} + \sum_{l=1}^{N_d} A_{11}^{*kl} \epsilon_x^l + B_{11}^{*kl} k_x^l \\
 M_x^k &= R_{11}^{*k} \epsilon_x^{\infty} + T_{11}^{*k} k_x^{\infty} + \sum_{l=1}^{N_d} B_{11}^{*kl} \epsilon_x^l + D_{11}^{*kl} k_x^l \quad k=1, \dots, N_d
 \end{aligned} \tag{13}$$

where, the superscript * indicates the effective laminate stiffnesses in free-flexure conditions. It is pointed out that the laminate stiffness terms in the above equations include condensed effects from all stiffness terms. In the case of pure (cylindrical) bending, the resultant constitutive equations are similar to eq. (13) but superscript * should be omitted.

Integrating the stress equilibrium equations through the thickness of the delaminated beam in the context of the described mechanics, the following equations of motion result:

$$\begin{aligned}
N_{xx}^o &= \rho^o \ddot{u}^o - \sum_{k=1}^{N_d} \rho^k \ddot{u}^k = 0 \\
M_{xx}^o &= q(x) - \rho^o \ddot{w}^o - \sum_{k=1}^{N_d} \rho^k \ddot{w}^k = 0 \\
N_{xx}^k &= \rho^k \ddot{u}^o - \sum_{l=1}^{N_d} \rho^l \ddot{u}^l = 0 \\
M_{xx}^k &= q^k(x) - \rho^k \ddot{w}^o - \sum_{l=1}^{N_d} \rho^l \ddot{w}^l = 0 \quad k=1, \dots, N_d
\end{aligned} \tag{14}$$

where: $q = \sigma_x(h) - \sigma_x(-h)$ and $q^k = \sigma_x(h) - \sigma_x(z_k)$ are the normal surface tractions applied on the upper and lower free surfaces; the overdot indicates differentiation with respect to time; ρ , ρ^k and ρ^k are the specific masses per unit area of the laminate and the delaminated sublaminates which are defined as follows:

$$\rho^o, \rho^k, \rho^k > = \sum_{j=1}^{N_l} \int_{h_j}^{h_{j+1}} \rho_j < 1, S(z-z_k), S(z-z_k)S(z-z_l) > dz \tag{15}$$

Combining eqs. (3-4), (13), and (14) the following system of differential equations results which describes the dynamic response of the delaminated beam:

$$\begin{aligned}
A_{11}^o \ddot{u}^o &- B_{11}^o \ddot{w}^o + \sum_{k=1}^{N_d} (P_{11}^k \ddot{u}^k - R_{11}^k \ddot{w}^k) = 0 \\
B_{11}^o \ddot{u}^o &- D_{11}^o \ddot{w}^o - \rho^o \ddot{w}^o + \sum_{k=1}^{N_d} (R_{11}^k \ddot{u}^k - R_{11}^k \ddot{w}^k - \rho^k \ddot{w}^k) = q(x) = 0 \\
P_{11}^k \ddot{u}^o &- R_{11}^k \ddot{w}^o + \sum_{l=1}^{N_d} (A_{11}^l \ddot{u}^k - B_{11}^l \ddot{w}^k) = 0 \\
R_{11}^k \ddot{u}^o &- T_{11}^k \ddot{w}^o - \rho^k \ddot{w}^o + \sum_{l=1}^{N_d} (B_{11}^l \ddot{u}^k - D_{11}^l \ddot{w}^k - \rho^l \ddot{w}^k) = q^k(x) = 0 \quad k=1, \dots, N_d
\end{aligned} \tag{16}$$

Note that eq. (16) may be applied to pristine laminates by setting $u^k = w^k = 0$, $N_d = 0$. In the following paragraphs, attention is focused on the case of a single delamination ($k=l=1$), however, the extension to multiple delaminations is straight forward. In either case, the fundamental solution for the above system of differential equations (16) has the form,

$$\{u^o, w^o, u^k, w^k\} = \{U^o, W^o, U^k, W^k\} e^{\lambda x} e^{j\omega t} \tag{17}$$

For a nontrivial solution of the previous form to exist in eqs. (16), the determinant of the resultant system should be zero which ultimately results in three characteristic equations relating the characteristic wavelength with the corresponding natural frequency of each mode. The first characteristic equation corresponds to the pristine sections (subscript 0), and the remaining two to the delaminated segment of the beam (subscripts 1 and 2) respectively, and all have the following form:

$$\lambda_o^4 L_o + \omega^2 M_o - \lambda_1^4 L_1 + \omega^2 M_1 - \lambda_2^4 L_2 + \omega^2 M_2 = 0 \quad (18)$$

where L_o, L_1, L_2 are strictly functions of the laminate stiffness terms and M_o, M_1, M_2 are functions of both the stiffness and mass terms in eq. (16). Two important conclusions are derived from eqs. (17) and (18). First, the admissible mode shapes of the beam for both pristine and delaminated sections have the form

$$\begin{Bmatrix} u^o \\ w^o \\ u^k \\ w^k \end{Bmatrix} = \{c_1^j\} e^{\lambda_j x} + \{c_2^j\} e^{-\lambda_j x} + \{c_3^j\} e^{i\lambda_j x} + \{c_4^j\} e^{-i\lambda_j x} + \{k_1^j\} x + \{k_2^j\}, \quad \lambda_j = \lambda_o, \lambda_1, \lambda_2 \quad (19)$$

where superscripts $j=0,1,2$ represent the various sections in the pristine and delaminated beam (see Fig. 2). Second, eqs. (19) indicate two types of admissible mode shapes, either global or local (in the delaminated region) modes. Due to space limitations, the paper is mostly restricted to global modes.

The 24 coefficients in eq. (19) are calculated from: boundary conditions at the proximal and distal end of the beam; continuity conditions for $w^o, w_x^o, u^o, N_x^o, M_x^o$, and N_{xz}^o at the proximal and distal tips of the delamination crack, that is,

$$\begin{aligned} w^o(x^-) &= w^o(x^+), & w_x^o(x^-) &= w_x^o(x^+), & u^o(x^-) &= u^o(x^+) \\ N_x^o(x^-) &= N_x^o(x^+), & M_x^o(x^-) &= M_x^o(x^+), & N_{xz}^o(x^-) &= N_{xz}^o(x^+) \end{aligned} \quad x=\alpha, \beta \quad (20)$$

and requirements that the relative interfacial motion diminishes ($w^k = w_x^k = u^k = 0$) at the proximal and distal tips of the delamination.

$$w^k(x) = w_x^k(x) = u^k(x) = 0 \quad x = \alpha, \beta \quad (21)$$

The axial location of the delamination is reflected in these boundary conditions. For a single crack, the above conditions together with the supporting conditions of the beam result in a linear system of 24 equations:

$$[F(\lambda_0, \lambda_1, \lambda_2)]\{C\} = 0 \quad (22)$$

where $\{C\}$ is the vector of the 24 unknown coefficients. For a nonzero solution, the determinant of the linear system (22) should be zero,

$$\det[F(\lambda_0, \lambda_1, \lambda_2)] = 0 \quad (23)$$

Combination of eqs. (18) and (23) provides the characteristic equation in terms of ω . The roots are the natural frequencies ω_n . Because of its size, the determinant in eq. (23) is numerically calculated using Cholesky decomposition. The characteristic eq. (23) is numerically solved for ω using a bisection technique, to find the natural frequencies. Then the corresponding characteristic wavelengths $\lambda_{0n}, \lambda_{1n}, \lambda_{2n}$ are determined from eq. (18). Subsequent substitution of the modal wavelengths λ_{in} into the system of linear equations (22), and solution of the system provides the coefficients for the mode shapes in the context of eq. (19). The axial location of the delamination is depicted in eqs. (19-21).

The modal damping of the beam is calculated as the ratio of the dissipated and maximum strain energy of the delaminated beam. The mode shapes and the corresponding generalized strains are calculated from eqs. (3), (4) and (19). The modal damping of the beam corresponding to the n-th mode is calculated from the ratio of the dissipated and maximum stored strain energy in the beam,

$$\eta_n = \frac{\int_0^l \delta W_L(x) dx + \int_0^l \delta W_f^k(x) dx}{2\pi \int_0^l W_L(x) dx} \quad (24)$$

where the dissipated strain energy at a point of the beam may involve a viscoelastic damping component provided by eq. (11), and a friction component δW_f from interfacial friction damping along the k th delamination. The maximum strain energy is provided by an analogous expression to eq. (11) involving the laminate stiffness matrices. However, the inclusion of the friction component due to the relative motion u^k requires additional work and development which exceeds the scope and space of this paper, and will be included in future work. Hence, the above formulation includes the effects of material, lamination, crack size and location on the viscoelastic damping of the beam, and the damping predictions in the following section correspond to changes in the viscoelastic damping of the beam in the presence of a delamination.

EXPERIMENTS AND MATERIALS

Because only limited experimental data are available in the open literature regarding the variation of natural frequencies and modal damping in delaminated composites, composite beam specimens with a simulated delamination crack were fabricated and tested. The beams had $[0/90/45/-45]_s$ and $[45/-45/90/0]_s$ laminate configurations respectively, with T300/934 graphite/epoxy plies with fiber volume ratio in the range of 0.57-0.63, and 0.005 in nominal thickness. A single delamination was artificially induced at the mid-plane of the composite using a teflon tape during the lay-up. Specimens with full-width delaminations and sizes of 0 (pristine), 1.2, 2.4 and 4.8 inches were fabricated. Two specimens were tested for each delamination length and laminate configuration type.

The beams were tested in a cantilever configuration, such that their free length was 11 in and the centers of the delamination cracks were always located at 5.0 in from the clamped end. The beam was

excited randomly with a "white" noise signal via an electromagnetic coil and a metallic chip (of practically negligible mass) adhered at the free-end of the beam. A miniature piezoelectric accelerometer was attached either near the clamped end, or near the mid-span at the free surface of the upper delaminated sublaminates. The voltage input to the coil and the output voltage of the accelerometer were supplied to a high-speed digital frequency analyzer, where they were digitally processed using FFT software to obtain the frequency response functions of the beam. The frequency response functions were further correlated in a least squares sense to a series of complex exponential terms (each one approximating an individual mode). Through this correlation, the modal frequencies and modal damping coefficients of the beam were extracted. The obtained experimental results are shown in the next section.

RESULTS AND DISCUSSION

This section presents predicted dynamic characteristics of delaminated composite beams and correlations with experimental data reported herein, as well as, with data reported by other researchers (Shen and Grady, 1992; Tracy and Pardo, 1989).

Assumptions

The elastic properties and the density of the T300/934 composite, which were used in the calculations are shown in Table 1. Some of the elastic composite properties were directly provided by the manufacturers' datasheet, the remaining ones were calculated from the properties of the constituent materials, as they were provided by the manufacturer, using micromechanics (Chamis, 1984). The longitudinal, transverse and in-plane shear damping (loss factors) of the composite (see Table 1) were extracted from unpublished damping measurements on off-axis specimens of the T300/934 composite³ using damping mechanics (Saravanan and Chamis, 1990). The mechanical

³ Private communication with Dr. J. M. Pereira, Structural Mechanics Branch, NASA Lewis Research Center, Cleveland, Ohio.

properties for the AS4/3501-6 graphite/epoxy composite (Tracy and Pardoen, 1989) were taken from the manufacturers datasheet.

[0/90]_{2s} Cantilever Beam

The predicted fundamental natural frequency of a [0/90]_{2s} T300/934 graphite/epoxy cantilever beam is shown in Fig. 3 together with reported measurements by Shen and Grady (1992). The beam had a central delamination of varying length (δl) located at the midplane, symmetrically about the mid-span of the beam. As seen in Fig. 3, excellent agreement was obtained between predicted and measured natural frequencies.

[90/45/-45/0]_{2s} Simply-Supported Beam

The first four natural frequencies of a [90/45/-45/0]_{2s} simply-supported AS4/3501-6 graphite/epoxy beam with a central delamination were also calculated and compared with average measured values reported by Tracy and Pardoen (1989). The variation of the natural frequencies as function of the crack length (δl) is shown in Fig. 4. Excellent agreement was obtained for all modes. These correlations validate further the capability of the method to provide reliable natural frequency predictions of delaminated beams.

[0/90/45/-45]_s Cantilever Beam

The previous cases involved doubly symmetric laminate configurations which result in negligible extension-flexure and flexure-twisting effects in the delaminated sublaminae. The subsequent cases investigate the free-vibration of delaminated composite beams with more general laminate configurations. The pristine laminate is symmetric and balanced, but the presence of a delamination produces unsymmetric and unbalanced sublaminae. Consequently, the following two cases entail dual objectives: to provide more severe testing of the developed mechanics; and to investigate

additional effects on the dynamic characteristics from the resultant asymmetries in the delaminated sublaminates.

The predicted and measured modal frequencies and damping of the pristine beam are shown in Table 2. Fig. 5 shows both the predicted and measured variations from the respective natural frequencies of the pristine beam as the crack length δl increases. In this and the remaining figures the solid line corresponds to the predicted results, while the symbols indicate the measured data corresponding to acceleration measurements at the root and the midspan of the beam. With the slight exception of the second bending mode, there is excellent agreement between predicted and measured results. The measured data of the first bending mode have shown consistent scatter in all experiments, which was attributed to imperfections in the supports. Similarly to the previous cases, the natural frequencies decrease as the delamination size increases.

The measured and predicted variations in the modal damping values for increasing delamination sizes are shown in Fig. 6. There is substantial scatter in the damping measurements for the first two bending modes, possibly because of imperfections and friction at the clamped end. There is also substantial scatter at large delamination cracks which may be attributed to losses occurring by interfacial friction and impacts (collisions) between the surfaces of the crack. However, the results for the third and fourth mode show good agreement between predictions and measurements. This indicates that the damping change at *small* and *medium* delamination sizes (approximately $d_0/l < 0.3$) is caused by the combined reductions in the flexural rigidity (matrix D), increases in the flexural laminate damping D_d and development of extension-flexure coupling, while the contribution of friction seems secondary. Friction effects at delamination interfaces seem to dominate the damping at high crack lengths (approximately $d_0/l > 0.3$).

The results also show that the damping of higher modes is more sensitive to the delamination presence, indicating that damping may be a better indicator of delamination damage especially in small and medium crack lengths.

[45/-45/90/0], Cantilever Beam

Predicted and measured natural frequencies and the corresponding modal damping for this laminate configuration are shown in Figs. 7 and 8 respectively. The modal frequencies and damping of the pristine beam are shown in Table 3. Contrary to the previous case, the effect of delamination on the modal damping magnitude change is modest. Again, excellent agreement between the developed mechanics and experiments was obtained for the natural frequencies with the exception of the second bending mode. The predicted changes in modal damping for the third and fourth mode exhibit fair agreement with the measured data, considering that friction effects are not included.

An interesting observation is that the viscoelastic damping may be also reduced depending on the mode order (see Fig. 8d). Such decreases may offset the friction damping and result in insignificant overall damping changes, thus complicating the crack detection. In order to explain the predicted and measured results, it is recalled that this (pristine) laminate configuration has low flexural rigidity but high damping. Therefore, the delamination induces smaller changes in the flexural rigidity which justify the modest changes in natural frequencies. The delaminated sublaminae have also lower flexural damping than the pristine configuration, because each has a 0° outer ply, which explains the observed modest damping changes and the decrease in the damping of the fourth mode.

Similarly to the previous case, the changes in the viscoelastic damping due to the presense of the delamination were shown to be significant. Thus, the present mechanics provide valuable understanding of the damping behavior of delaminated composite structures. Finally, in both laminate configurations small delamination cracks (less than 10% of beam span) may not be detectable by monitoring global modal characteristics of the beam, in such cases, other local parameters should be monitored via distributed sensors.

CONCLUSIONS

Novel mechanics for the dynamic response of composite laminates with delamination cracks were developed and described in this paper. The kinematic assumptions allow for in-plane and out-of-plane relative motion between the delaminated sublaminates, and are applicable to general laminate configurations. Based on this generalized laminate theory, an exact methodology was developed for predicting and relating the natural frequencies, mode shapes and modal damping of composite beams of general laminations and boundary conditions with the delamination damage. The mechanics described herein were encoded and integrated with micromechanical models to provide an unified computer code for the analysis of delaminated composite beams.

The effects of delaminations on the dynamic characteristics of composite laminates, including damping, were investigated analytically and experimentally. Experiments were conducted on composite beams with induced delaminations and measured natural frequencies and modal damping were reported. The correlations between predicted and measured data have shown excellent agreement for the case of natural frequencies and fair agreements for the case of modal damping. This agreement illustrates the accuracy and versatility of the mechanics.

Both analytical and experimental results provided valuable insight to the interactions between structural response and delamination damage. The effects of delamination on the dynamic characteristics are very dependent on the laminate configuration, and should be more profound in laminates with complex laminations. In such cases, rapid and significant damping changes may provide reliable indication of delamination damage and growth, in connection with decreases in natural frequencies. It was also found that natural frequencies are rather insensitive to interfacial friction. At small delamination sizes changes in damping were caused primarily from changes in the viscoelastic laminate damping of the structure, while interfacial friction damping became important at large delamination cracks. Future work will be focused on the inclusion of friction effects to the mechanics.

ACKNOWLEDGEMENT

The authors want to thank Dr. Benjamin B. Choi of NASA-Lewis Research Center for his assistance in conducting the experimental work.

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Table 1. Mechanical properties of T300/934 composite (0.57 FVR).

<i>Moduli</i>	<i>Density</i>	<i>Loss Factors (%)</i>
$E_{111} = 18.5$ Mpsi	$\rho = 0.057$ lb/in ³	$\eta_{111} = 0.255$
$E_{222} = 1.7$ Mpsi		$\eta_{222} = 0.80$
$G_{112} = 0.7$ Mpsi		$\eta_{112} = 1.35$
$\nu_{112} = 0.24$		

Table 2. Natural frequencies and modal damping of pristine [0/90/45/-45]_s Beam

	Mode 1	Mode 2	Mode 3	Mode 4
<i>Natural Frequency, Hz</i>				
Measured (Stand. Deviation)	17.75 (0.233)	110.3 (3.34)	318.7 (2.79)	611.7 (15.2)
Predicted	18.17	113.8	318.7	624.2
<i>Loss Factor (%)</i>				
Measured (Stand. Deviation)	2.350 (0.110)	0.634 (0.102)	0.302 (0.020)	0.489 (0.085)
Predicted	0.288	0.288	0.288	0.288

Table 3. Natural frequencies and modal damping of pristine [45/-45/90/0]_s Beam.

	Mode 1	Mode 2	Mode 3	Mode 4
<i>Natural Frequency, Hz</i>				
Measured (Stand. Deviation)	10.29 (0.159)	65.4 (1.87)	188.3 (1.04)	367.2 (8.23)
Predicted	9.70	60.7	170.2	333.8
<i>Loss Factor (%)</i>				
Measured (Stand. Deviation)	5.48 (1.38)	1.56 (0.674)	1.01 (0.032)	1.006 (0.020)
Predicted	0.648	0.648	0.648	0.648

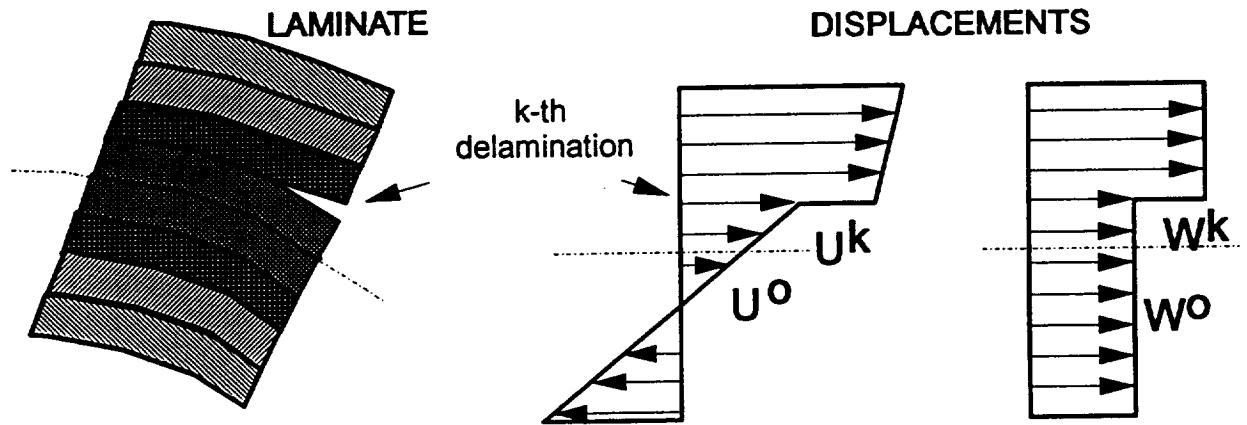


Fig. 1 Kinematic assumptions of generalized laminate theory.

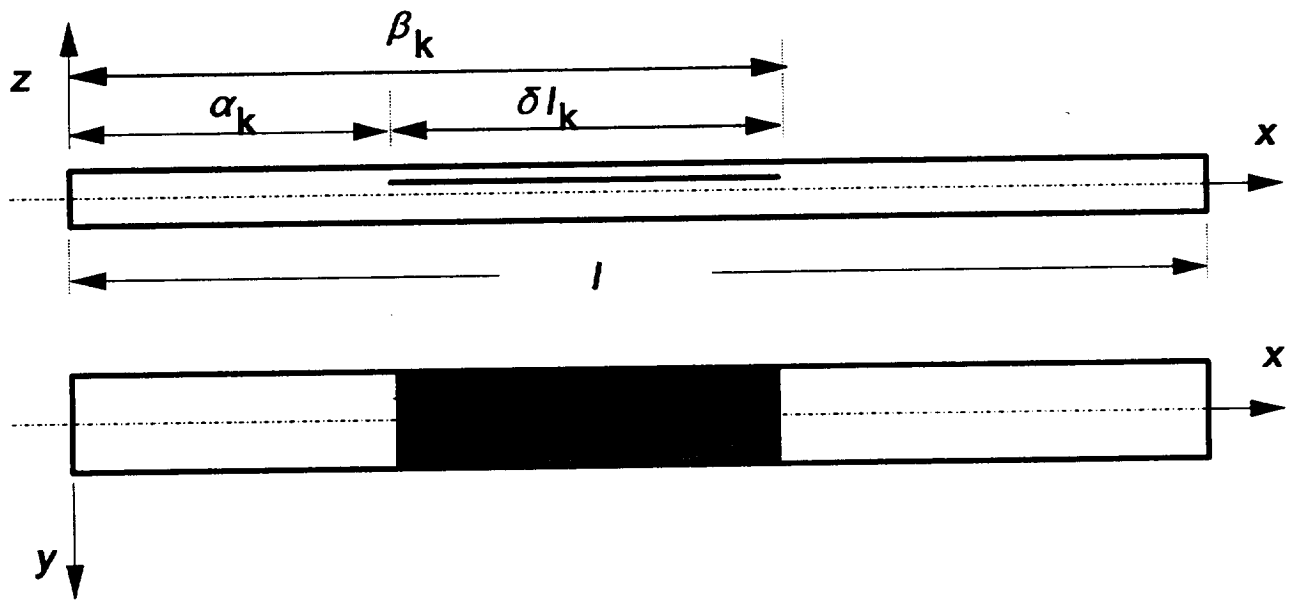


Fig. 2 Typical composite beam with interply delamination cracks.

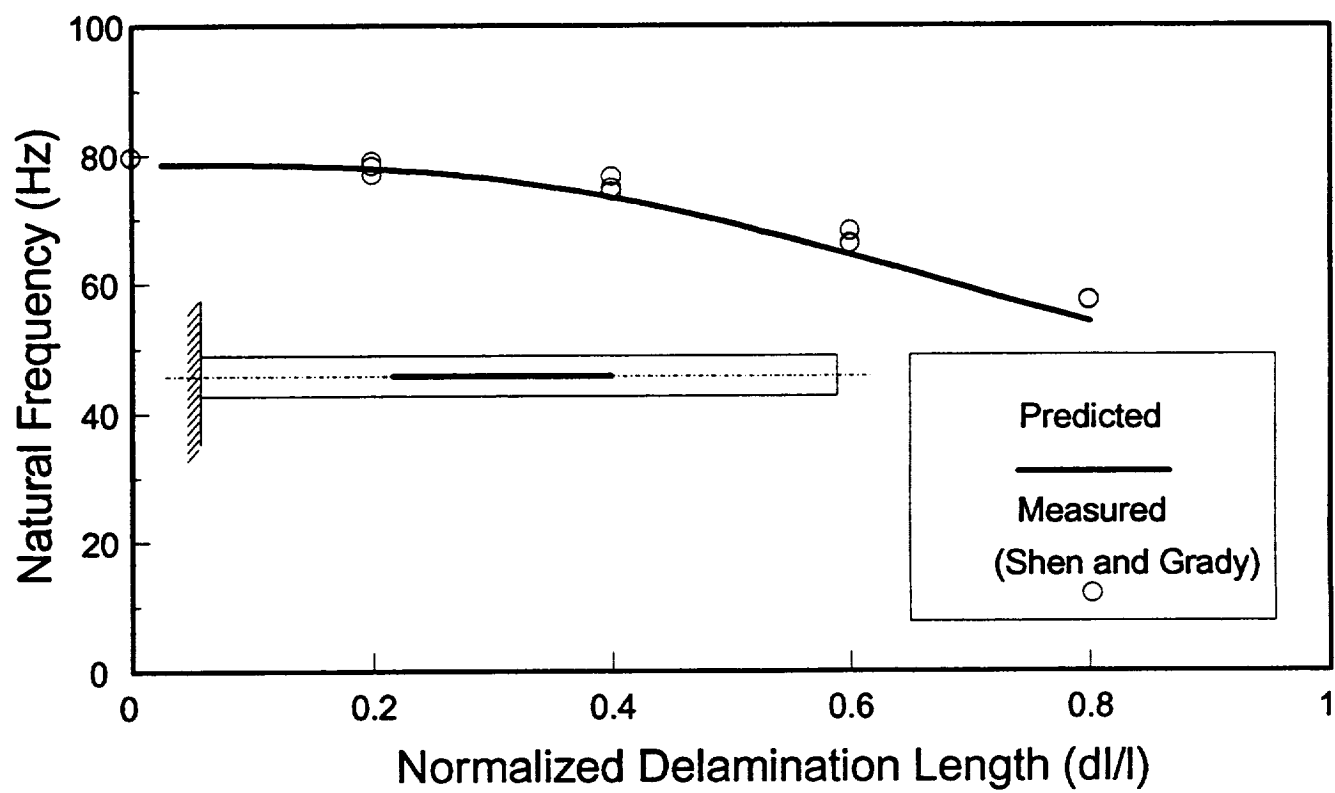


Fig. 3 Predicted effect of a central delamination on the fundamental natural frequency of a $[0/90]_{2s}$ cantilever beam. Measurements by Shen and Grady (1992).

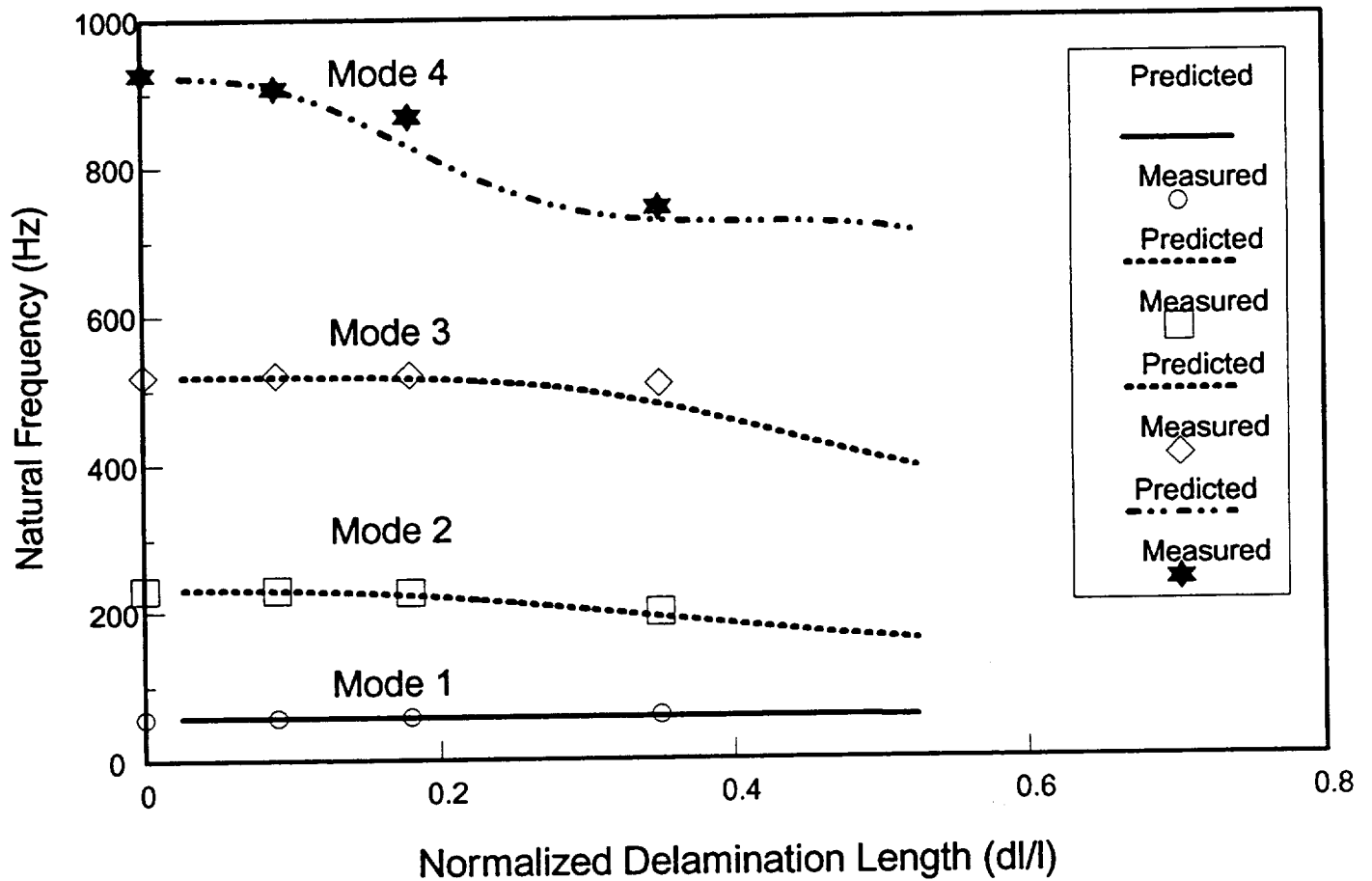


Fig. 4 Predicted effect of a central delamination on the natural frequencies of a $[90/45/-45/0]_{2s}$ simply-supported beam beam. Measurements by Tracy and Pardoen (1989).

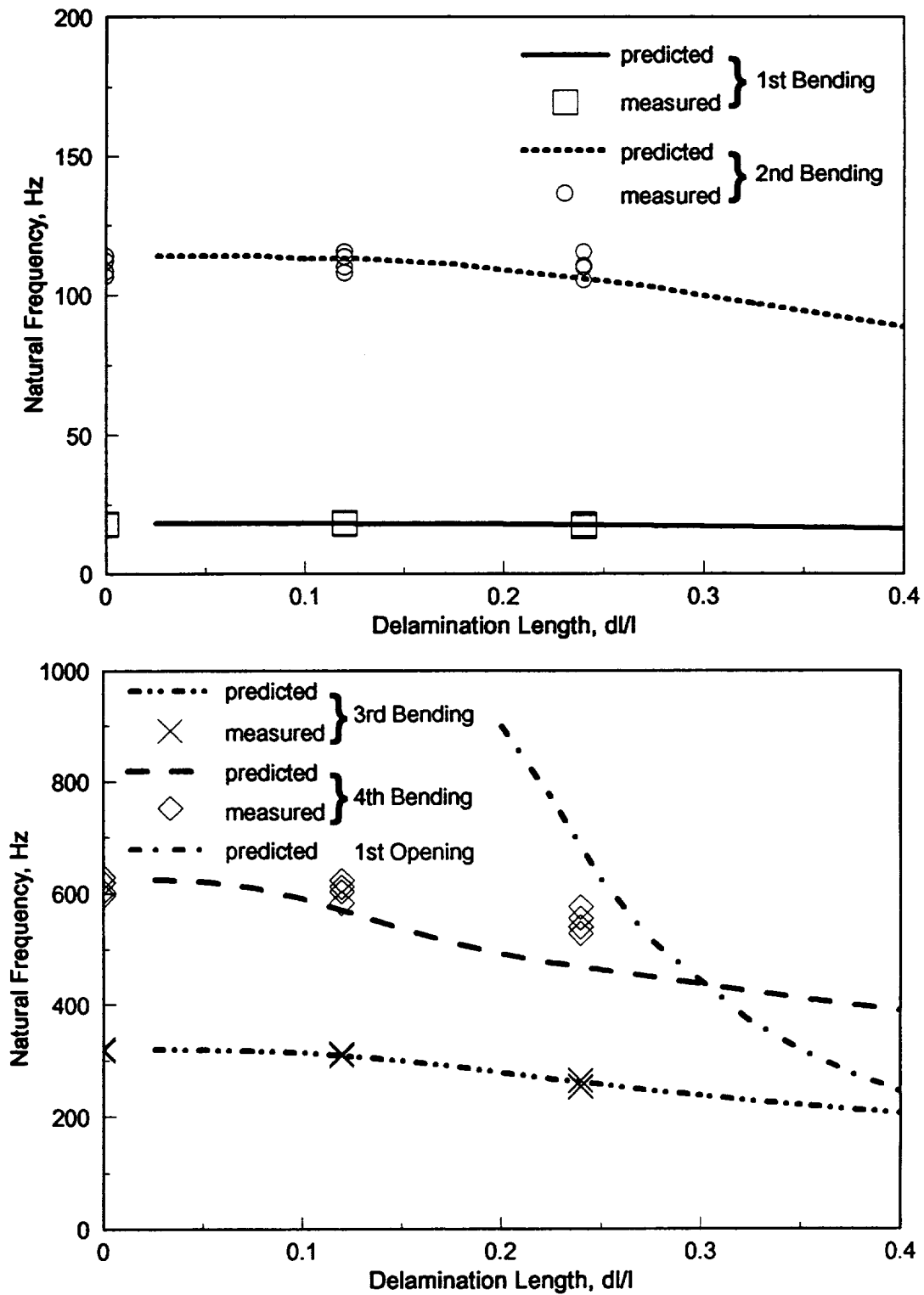


Fig. 5 Effect of a delamination size on the natural frequencies of the $[0/90/45/-45]_2$ cantilever beam.

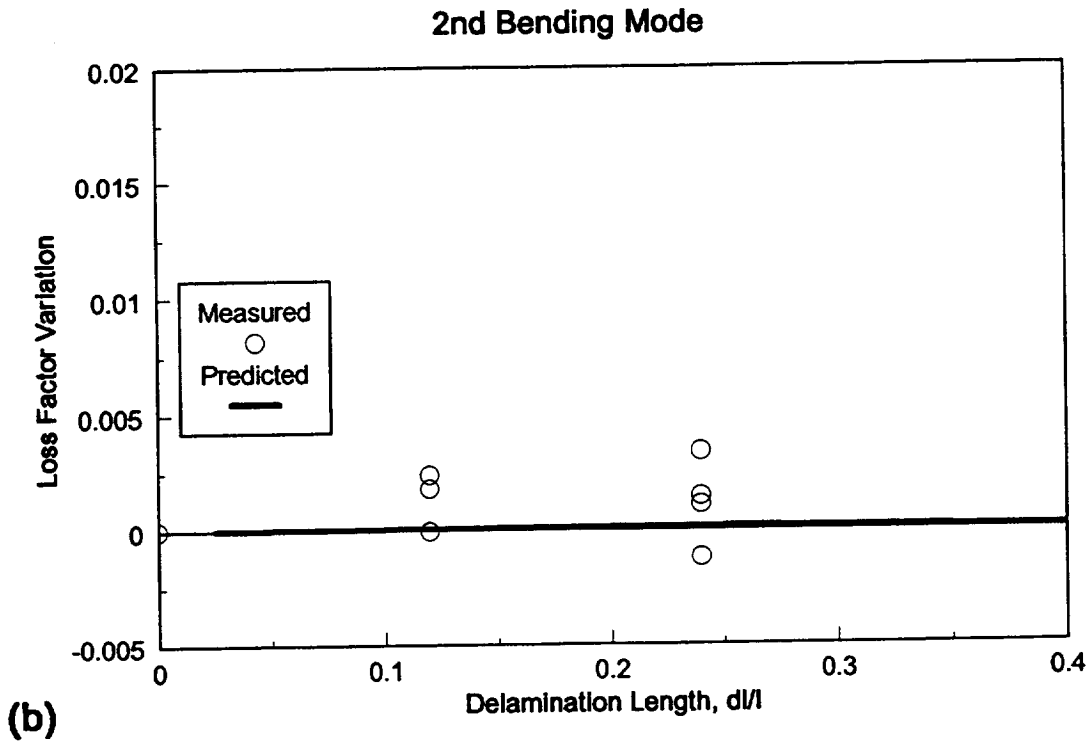
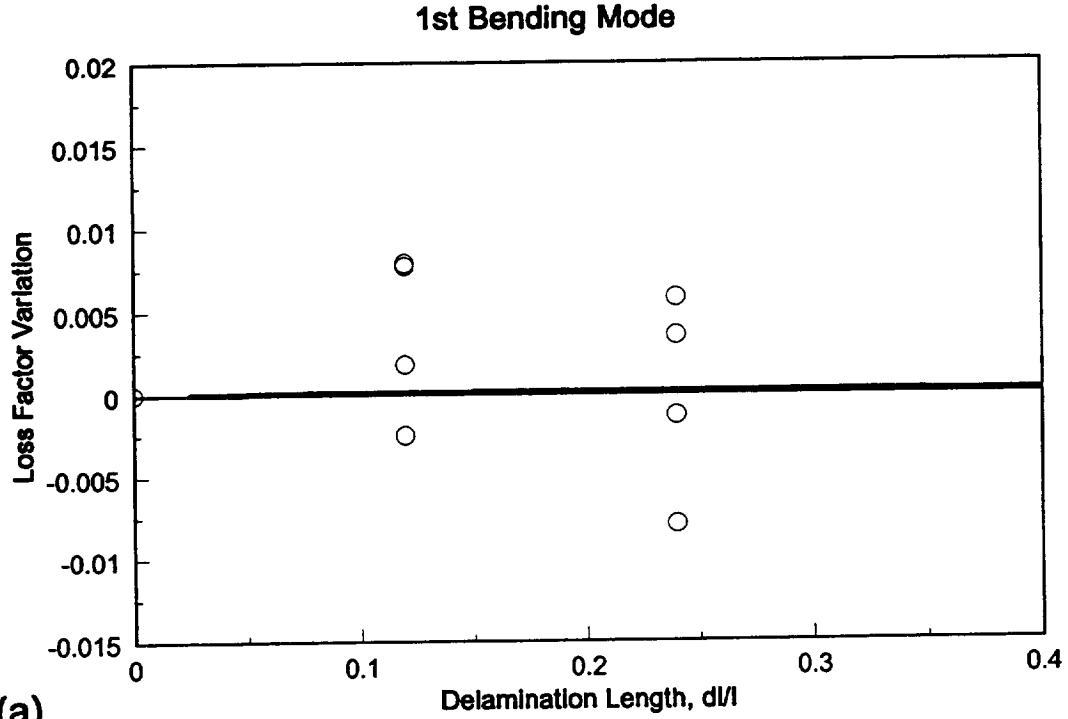
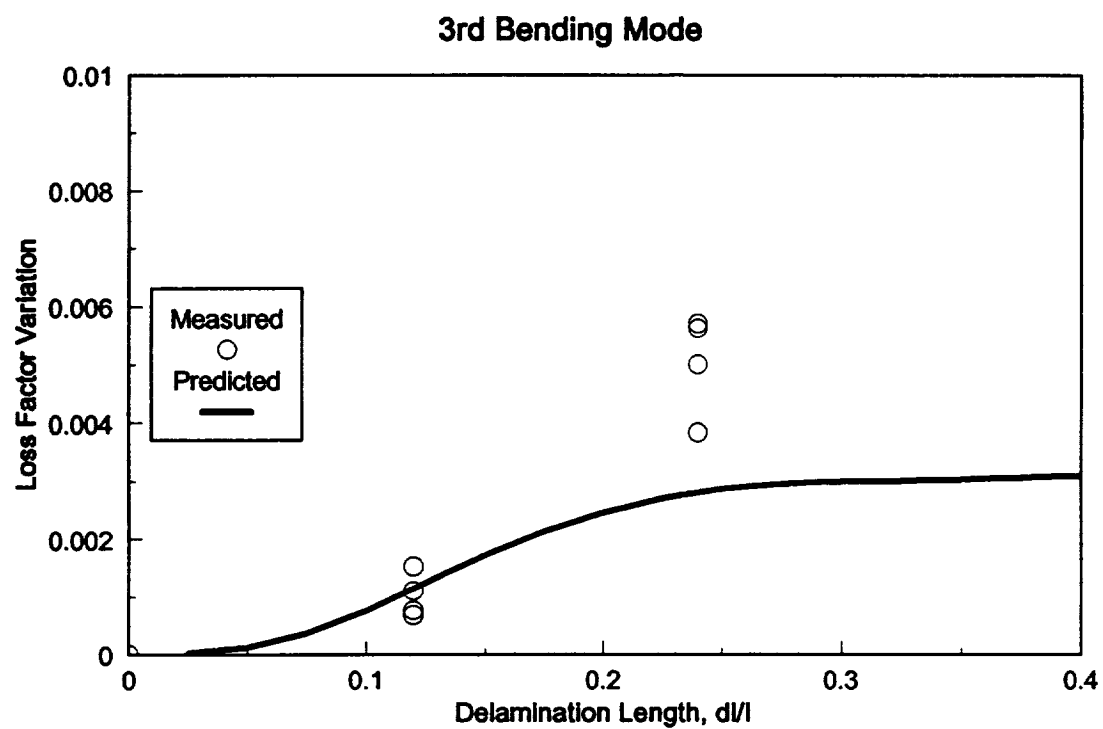
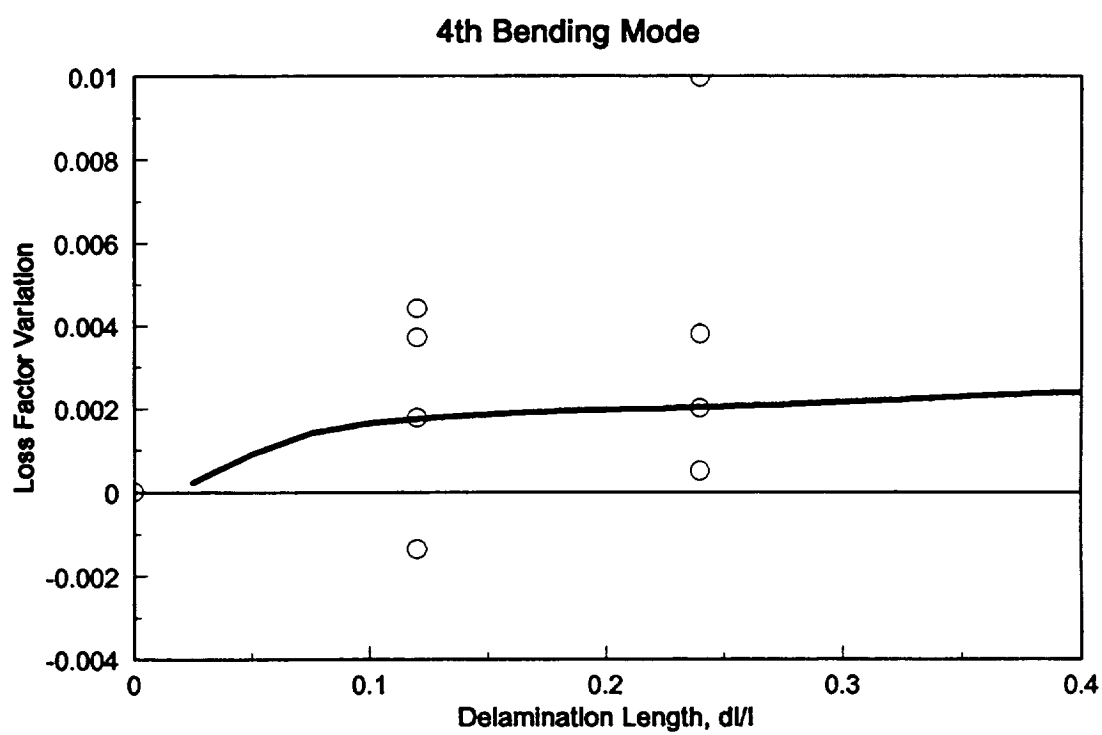


Fig. 6 Effect of a delamination size on the modal damping of the $[0/90/45/-45]_2$ cantilever beam. (a) first bending mode; (b) second bending mode; (c) third bending mode; (d) fourth bending mode.



(c)



(d)

Fig. 6 Concluded. (c) third bending mode; (d) fourth bending mode.

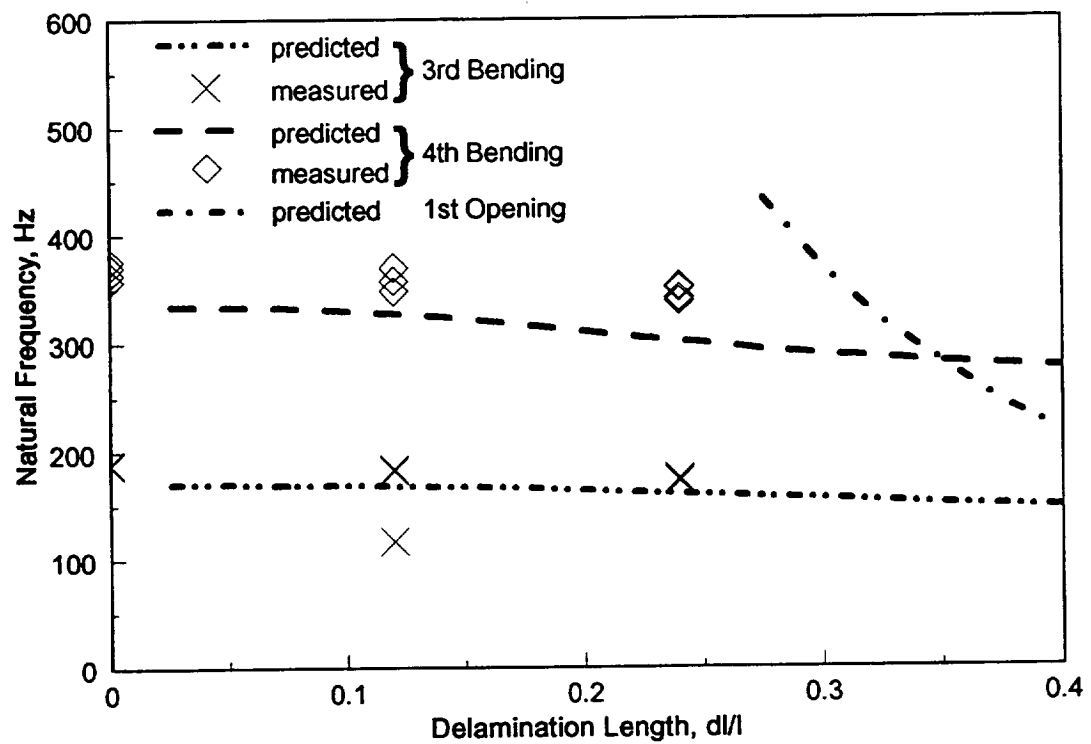
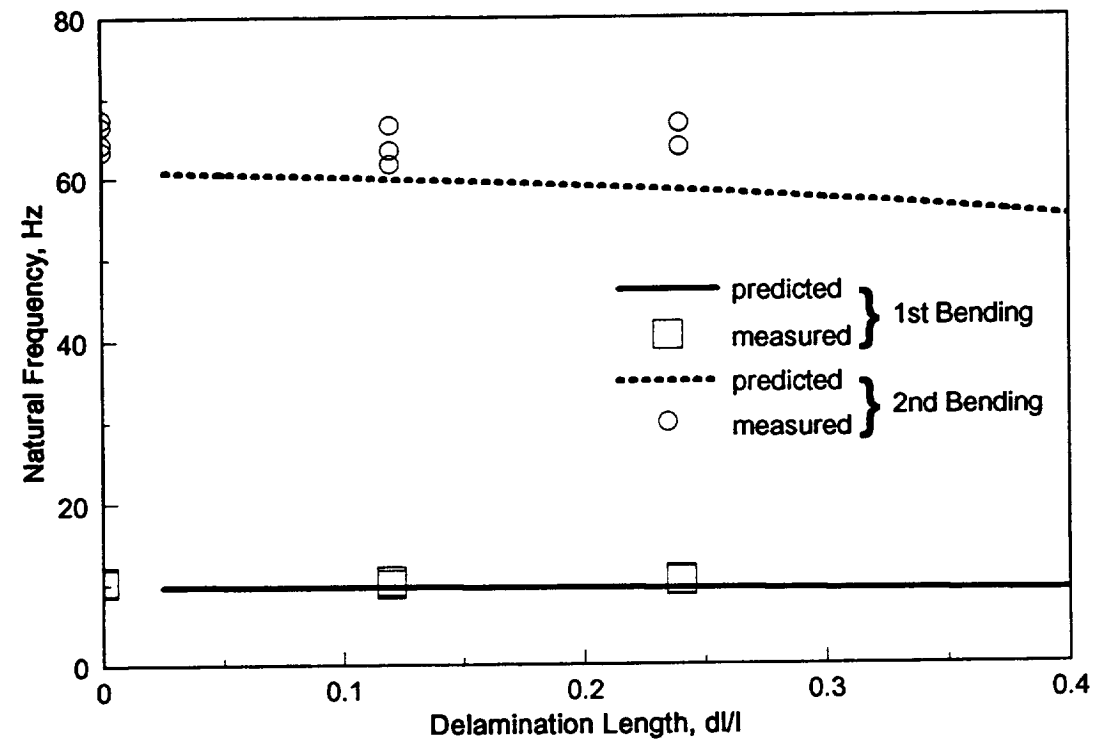


Fig. 7 Effect of a delamination size on the natural frequencies of the $[45/-45/90/0]_2$ cantilever beam.

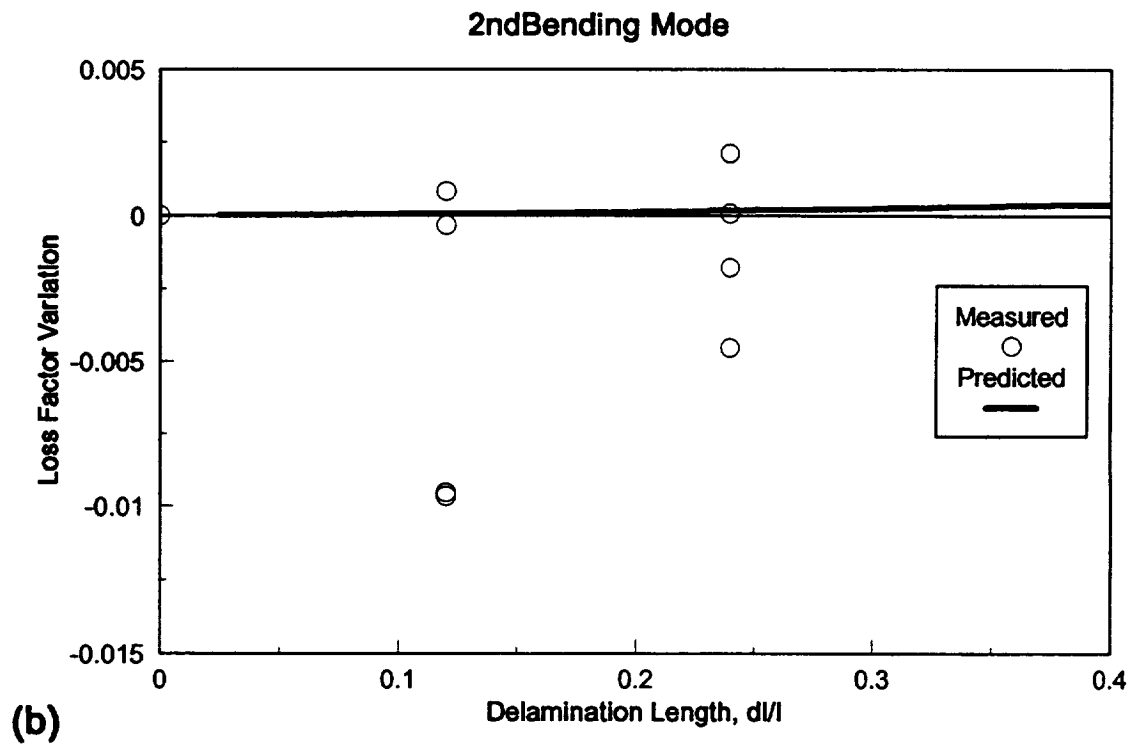
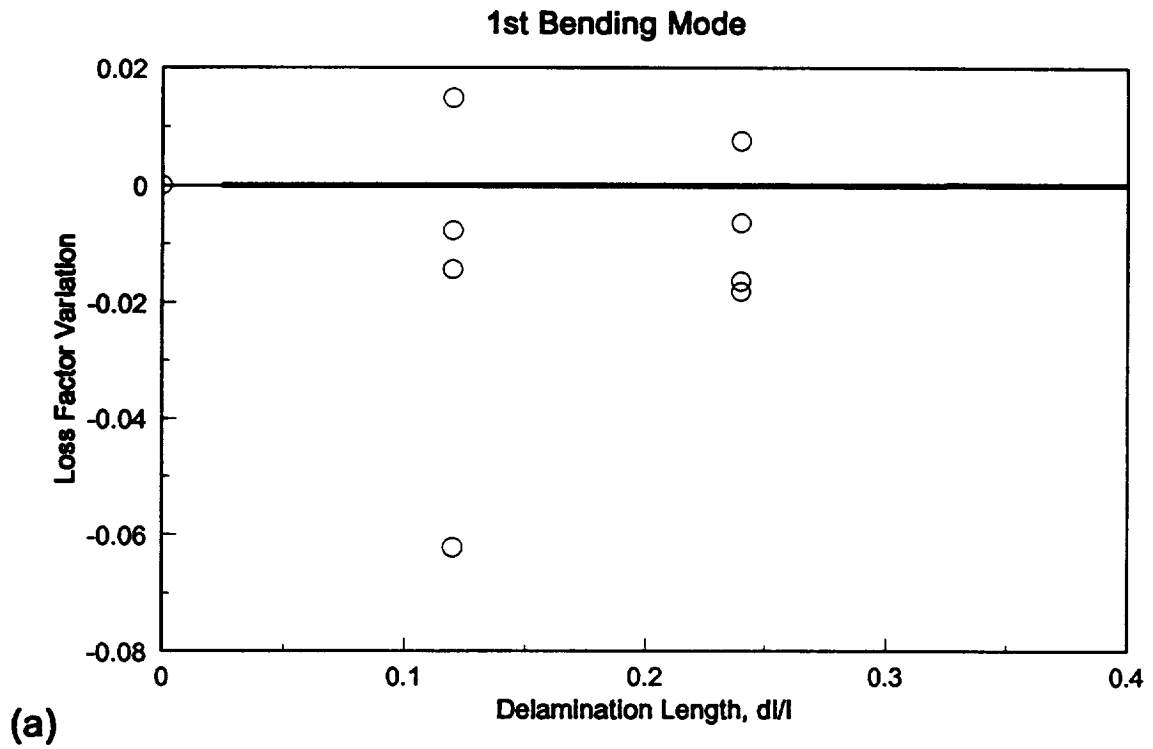
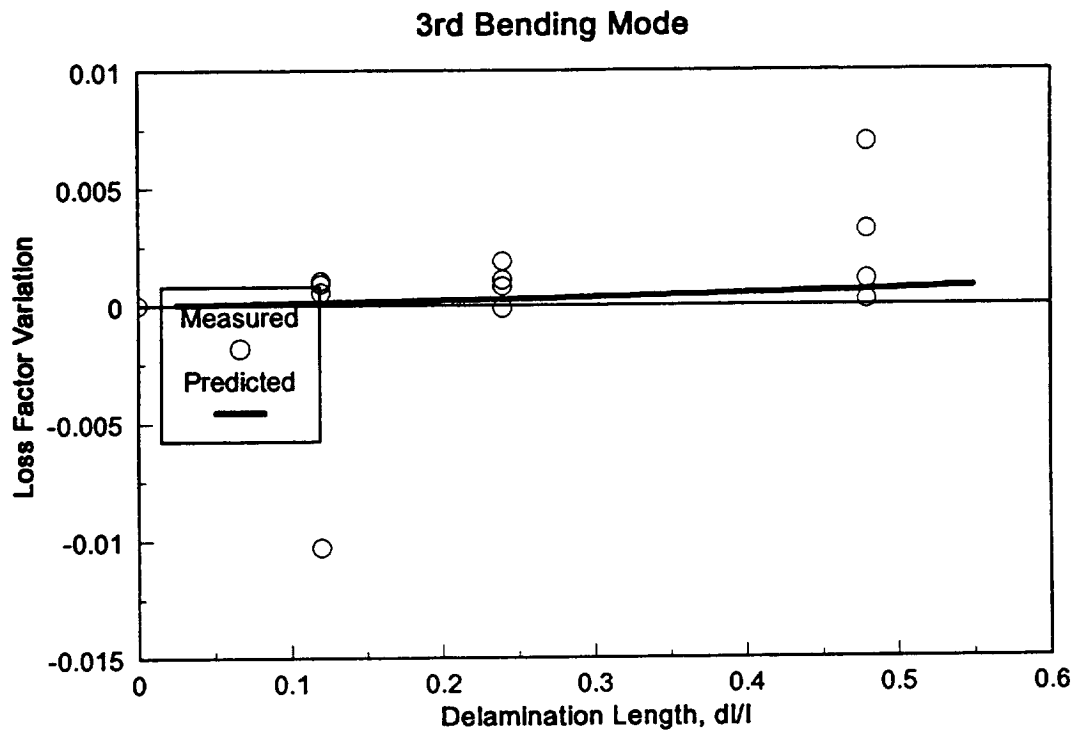
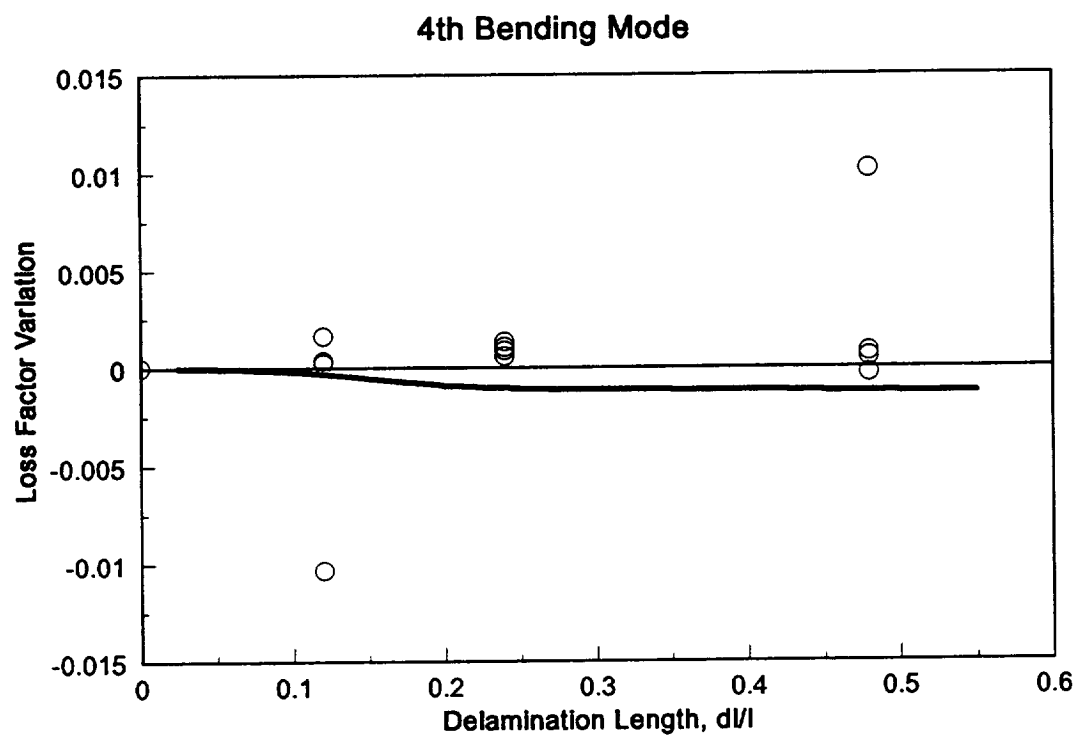


Fig. 8 Effect of a delamination size on the modal damping of the $[45/-45/90/0]_2$ cantilever beam. (a) first bending mode; (b) second bending mode; (c) third bending mode; (d) fourth bending mode.



(c)



(d)

Fig. 8 Concluded. (c) third bending mode; (d) fourth bending mode.

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE February 1995	3. REPORT TYPE AND DATES COVERED Technical Memorandum		
4. TITLE AND SUBTITLE Effects of Delaminations on the Damped Dynamic Characteristics of Composite Laminates: Mechanics and Experiments		5. FUNDING NUMBERS WU-505-63-5B		
6. AUTHOR(S) D.A. Saravanos and D.A. Hopkins				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135-3191		8. PERFORMING ORGANIZATION REPORT NUMBER E-9467		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, D.C. 20546-0001		10. SPONSORING/MONITORING AGENCY REPORT NUMBER NASA TM-106862		
11. SUPPLEMENTARY NOTES Responsible person, D.A. Saravanos, organization code 5210, (216) 433-8466.				
12a. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified - Unlimited Subject Category 24 This publication is available from the NASA Center for Aerospace Information, (301) 621-0390.		12b. DISTRIBUTION CODE		
13. ABSTRACT (Maximum 200 words) Analytical and experimental work is presented on the damped free-vibration of delaminated laminates and beams. A laminate theory is developed where the unknown kinematic perturbations induced by a delamination crack are treated as additional degrees of freedom. The generalized stiffness, inertia and damping matrices of the laminate are formulated. An analytical solution is developed for the prediction of natural frequencies, modes and modal damping in composite beams with delamination cracks. Evaluations of the mechanics on various cantilever beams with a central delamination are performed. Experimental results for the modal frequencies and damping of composite beams with a single delamination are also presented and correlations between analytical predictions and measured data are shown. The effects of delamination vary based on crack size, laminate configuration, and mode order. The implications of the mechanics in developing delamination detection techniques are also discussed.				
14. SUBJECT TERMS Composite materials; Laminates; Beams; Cracks; Delaminating; Dynamic characteristics; Damping; Vibration; Nondestructive tests; Health monitoring		15. NUMBER OF PAGES 34		
		16. PRICE CODE A03		
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT	